

Impacts of tropical cyclones on episodic transport of water and suspended sediment in mountainous catchments: A case study from Hainan Island

Caifeng Liu^a, Wei Jiang^{a,*}, Shanshan Deng^a, Yangyang Yong^a, Tingwu Gu^a, Yuchen Shi^b, Siqu Du^a, Ting Yang^a, Kefu Yu^{a,c}

^a Guangxi Laboratory on the Study of Coral Reefs in the South China Sea, School of Marine Sciences, Guangxi University, Nanning, 530004, China

^b School of Resources, Environment and Materials, Guangxi University, Nanning, 530004, China

^c Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou, 528315, China

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ABSTRACT

Study region: Hainan Island, China, focusing on three major rivers: the Nandu, Changhua, and Wanquan River basins.

Study focus: Tropical cyclones (TCs) are key drivers of episodic riverine material fluxes in coastal mountainous regions. However, their quantitative role in regulating water discharge and suspended sediment discharge (SSD) in tropical island basins remains poorly constrained. Based on 64 years (1960–2023) of daily hydrological records, this study quantifies TC-associated contributions to water discharge and SSD and examines how TCs modify water–sediment transport.

New hydrological insights for the region: Quantitative analysis indicates that TCs exert a substantial influence on water discharge and SSD, contributing $4 \pm 4\%$ to $8 \pm 6\%$ of annual water discharge and $11 \pm 10\%$ to $30 \pm 27\%$ of annual SSD on average, with contributions reaching 91–95% of SSD in extreme years. Their influence on SSD is markedly stronger than on water discharge, indicating a pronounced sediment-routing enhancement. Sensitivity to TC forcing varies substantially across basins and these inter-basin differences are jointly regulated by TC characteristics, basin geomorphology (such as area and slope), and reservoir regulation. The identified water–sediment response regimes further highlight the nonlinear nature of sediment transport under TC forcing. These findings refine the understanding of extreme-event-driven material fluxes and provide a critical basis for managing flood risks, reservoir operations, and soil conservation in tropical island river systems.

1. Introduction

Tropical cyclones (TCs) represent a powerful expression of coupled atmosphere–ocean dynamics, with impacts extending far beyond their immediate societal and economic disruption to fundamentally alter coastal landscapes and biogeochemical cycles (Bhattacharya et al., 2025). As dominant agents of episodic disturbance, these storms deliver intense rainfall (Zhong et al., 2026), contributing 35–50% of total annual precipitation in affected regions (Khouakhi et al., 2017) and driving extreme runoff that can

* Corresponding author at: Guangxi Laboratory on the Study of Coral Reefs in the South China Sea, Guangxi University, Nanning 530004, China.
E-mail address: jianwe@gxu.edu.cn (W. Jiang).

reshape river mouth morphology (Woodruff et al., 2013). The associated physical forcing, including strong wind-driven vertical mixing, can replenish nutrients and enhance primary productivity in coastal waters (Da et al., 2021). Crucially, TC-generated floods mobilize vast quantities of terrestrial sediment, which is subsequently delivered to wetlands, lagoons, and coral reefs, often triggering severe seabed erosion and damaging benthic communities (Ramos-Scharrón et al., 2021). This pulsed delivery of water and sediment represents an important control on the evolution of estuaries and the health of coastal ecosystems (Jorquera et al., 2024). Consequently, cyclone-driven water and sediment transport processes have become key focus of research on river-coastal systems in the context of global change. However, a quantitative, process-based understanding of how TCs contribute to and modulate water discharge and suspended sediment discharge (SSD) across basins with diverse characteristics remains incomplete. Such knowledge is vital for predicting landscape responses under changing climate regimes and for managing risks to soil, water resources, and infrastructure (Lin et al., 2013). Here, we address this gap by systematically quantifying the contribution of TCs to water discharge and sediment transport of mountainous rivers in Hainan Island, and by elucidating the key basin factors that regulate these extreme episodic fluxes.

Human activities, particularly the construction of dams and reservoirs, have become a major control on global riverine sediment fluxes, often attenuating natural climatic signals by trapping sediment and altering flow regimes (Dai et al., 2016; Dethier et al., 2022; Moragoda et al., 2023). Studies indicate that, globally, approximately 3.6 billion tons of sediment are retained in reservoirs annually from rivers with catchment areas greater than 100 km², leading to a significant reduction in sediment transport to downstream and estuarine regions (Chen et al., 2018). Iconic examples include the near-complete (98%) cessation of sediment delivery to the Nile Delta following the construction of the Aswan High Dam (Abd-El Monsef et al., 2015), and a > 70% reduction in the sediment load of the Yangtze River after the commissioning of the Three Gorges Dam (Chen et al., 2021), with similar patterns observed for the Colorado, Mississippi, and Yellow rivers (Ji et al., 2022). In addition to sediment retention by reservoirs, human activities such as vegetation restoration, soil and water conservation, and land-use changes have altered the surface conditions within river basins (Bai et al., 2024; Shi et al., 2022; Zhang et al., 2023). By reducing slope erosion and delaying the runoff process, these activities further diminish sediment production and transport capacity (Sun et al., 2024). Nevertheless, such long-term suppression of sediment supply does not necessarily preclude episodic sediment mobilization during extreme events. In steep tropical and subtropical basins, intense precipitation associated with TCs can trigger widespread shallow landslides, rapidly mobilizing large quantities of hillslope material and delivering substantial sediment loads to stream networks (Ramos-Scharrón et al., 2021). Against this backdrop of widespread anthropogenic sediment depletion, the pulsed delivery of water and suspended sediment by TCs gains critical importance, as these extreme events can temporarily reactivate fluvial sediment transport and substantially influence annual or even decadal material budgets.

In recent years, there has been a growing body of research on the impact of TCs on river sediment transport. Existing studies generally agree that tropical cyclone events can substantially exacerbate erosion and sediment discharge in watersheds through short-duration, intense rainfall. In some watersheds, they account for the majority of annual sediment transport (Darby et al., 2016; Li et al., 2020). In Taiwan, approximately 75% of the long-term suspended sediment transport from major rivers occurs within only a small fraction of the time and is closely associated with typhoon-driven extreme events, during which sediment concentrations can reach hyperpycnal levels (>40 g/L) (Deng et al., 2019). Similar phenomena have been confirmed in watersheds in the Philippines, Vietnam, and the Caribbean islands (Darby et al., 2016; Larsen and Webb, 2009). These studies focus on quantifying the bulk contribution of TCs to total flux but seldom interrogate how TCs fundamentally alter sediment transport dynamics specifically, the intrinsic relationship between water discharge and SSD (the water–sediment regime). Previous studies have shown that under extreme rainfall conditions, river sediment transport processes may exhibit nonlinear responses, with sediment transport efficiency changing markedly with variations in rainfall intensity and watershed conditions (Jing et al., 2025; Xu et al., 2021; Zhang et al., 2018). In the Huangfuchuan watershed, extreme rainfall indices show significant correlations with sediment load before 1998, but later this relationship weakens, indicating a nonlinear sediment–rainfall link once human modifications and vegetation recovery intervene (Li, 2024). At a broader scale, global observations show that precipitation erosivity, land-cover change, and dam trapping can jointly reshape fluvial suspended-sediment concentrations and fluxes (Sun et al., 2025). Lepesqueur et al. noted that sediment sources, grain size composition, and transport pathways all undergo significant changes during extreme events (Lepesqueur et al., 2019). However, there remains a lack of systematic understanding regarding how tropical cyclones of varying intensities influence water–sediment coupling, as well as how watershed topography, reservoir regulation, and land-use changes collectively affect sediment transport dynamics. Furthermore, a large number of current studies are based on analyses of single typhoon events or short time series. While these studies can reveal instantaneous water and sediment responses during tropical cyclones, they struggle to disentangle the forcing of TCs from low-frequency climate variability (e.g., El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO)). Previous studies have shown that ENSO can modulate the location and rapid intensification of TCs in the northwestern Pacific (Guo and Tan, 2018), while interdecadal Pacific variability influences the long-term spatial distribution of North Pacific TC tracks (Zhao et al., 2020). More recently, multidecadal variability in TC precipitation in southeastern China has been linked to the PDO (Wang et al., 2025). However, there remains considerable uncertainty regarding the stability of the long-term contribution of tropical cyclones to river water and sediment transport, as well as the underlying climate-modulating mechanisms. Finally, although tropical cyclone-driven sediment transport has been investigated in large continental systems such as the Mekong and in several well-studied mountainous or island catchments, long-term, multi-event analyses of smaller, flashier mountainous rivers remain comparatively limited, despite their high sensitivity to extreme events (Darby et al., 2016; Yang et al., 2022).

In a warming climate, TCs are projected to increase in both intensity and duration, with observational evidence indicating a poleward shift in their tracks that may expose new coastal regions to heightened risk (Studholme et al., 2022; Sugi et al., 2017; Wang et al., 2020). These evolving characteristics compound the inherent complexity of TC impacts. As highly dynamic and spatially

asymmetric events, individual cyclones can generate markedly different sediment fluxes and seabed responses depending on their path, intensity, and associated rainfall distribution (Chi et al., 2023; Xu et al., 2025). This path- and intensity-dependent heterogeneity in sediment dynamics remains poorly quantified, introducing major predictive uncertainties. Consequently, advancing from a bulk quantification of TC-driven sediment flux to a mechanistic understanding of how specific TC attributes control spatial patterns of erosion and deposition is imperative. Such knowledge is foundational for developing robust predictive models of coastal morphological change and for informing adaptive risk management strategies for vulnerable communities and ecosystems facing an altered future storm regime.

Hainan Island, situated in the South China Sea, represents a critical and dynamic natural laboratory for studying TC-land interactions. As one of China's most frequently and severely impacted regions, it experiences a high density of landfalling TCs—136 events directly influenced its river systems between 1960 and 2023. Its distinctive geomorphology, characterized by a central mountainous core (e.g., Wuzhi Mountain) and radially distributed, short-steep rivers (Nandu River, Changhua River, and Wanquan River), predisposes its catchments to rapid, flashy hydrological responses to TC-driven extreme rainfall. This intrinsic sensitivity is further modulated by decades of human activity, notably through the construction of major reservoirs (e.g., Songtao), which alter natural flow and sediment regimes. This confluence of intense natural forcing, responsive landscape, and anthropogenic intervention makes Hainan an ideal setting to disentangle the complex drivers of episodic water and sediment fluxes. However, a systematic, long-term, and comparative multi-basin assessment of TC-induced changes in water–sediment coupling across the island's major rivers remains absent.

To address this gap, we leverage a 64-year (1960–2023) dataset encompassing daily water discharge, SSD, precipitation, and TC tracks, centered on five key hydrological stations (Jiaji (JJ), Longtang (LT), Baoqiao (BQ), Jiabao (JB), Santan (ST)) across the three major rivers. Employing a suite of methods including hydrological event separation, sediment rating curves, contribution quantification, and wavelet analysis, this study is designed to resolve three core questions: 1) Identify the long-term spatiotemporal variation patterns of water discharge and sediment transport in Hainan's principal rivers under TC influence. 2) Quantitatively partition the contribution of TCs to the annual water discharge and SSD of these distinct river systems. 3) Investigate the mechanisms through which local factors—such as reservoir regulation and basin slope—modulate the sensitivity of riverine water–sediment processes to TC forcing.

2. Research area, data and methods

2.1. Research area

Hainan Island serves as a critical natural laboratory for investigating TC-land interactions, being among China's most frequently impacted and severely affected regions (Jiani et al., 2022). With an average of 2.7 landfalls annually—a frequency second only to Guangdong—and a humid tropical climate (mean annual temperature $\sim 24.9^{\circ}\text{C}$; precipitation $\sim 2014\text{ mm}$), the island is routinely subjected to intense, TC-driven rainfall events often exceeding hundreds of millimeters. Its distinctive dome-shaped topography, with a central mountainous core encircled by plateaus and plains, has given rise to a radial drainage network. Three principal rivers—the Nandu River (334 km; 7033 km^2), Changhua River (232 km; 5150 km^2), and Wanquan River (163 km; 3693 km^2)—drain 47% of the island's area and flow independently into the South China Sea. These basins are characterized by steep upland gradients, flashy

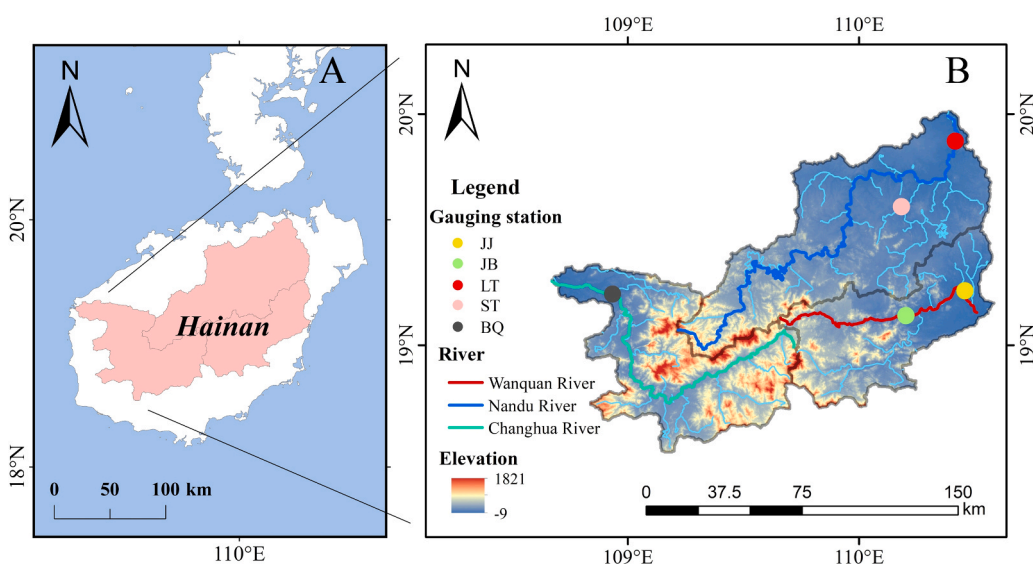


Fig. 1. Location map of the three major river basins on Hainan Island and the selected hydrological stations. (A) Location of the study watershed on Hainan Island. (B) Elevation distribution, river network, and hydrological gauging stations within the watershed.

hydrological responses, and a pronounced monsoon-driven flood season (July–October), during which TC events trigger extreme pulses of water discharge and suspended sediment transport. From 1960–2023, 136 TCs directly influenced these river systems. Given that the suspended sediment data at some hydrological stations of the three rivers are incomplete, and the stations located near the river mouths can better capture the impact of tropical cyclones on the water and sediment transport of the rivers, we focus on five key hydrological stations near the tidal limits: LT and ST on the Nandu River, BQ on the Changhua River, and JJ and JB on the Wanquan River (Fig. 1). These stations were selected based on geographic representativeness and data completeness to quantify downstream fluxes from each basin.

2.2. Data sources

The data used in the paper mainly include river discharge data, SSD data, precipitation data, typhoon data, and data from large-scale reservoirs. The daily measured water discharge data and daily measured SSD data of the Nandu River, Changhua River, and Wanquan River on Hainan Island, as well as the precipitation data, were collected from the Hydrology and Water Resources Survey Bureau of Hainan Province (<https://swt.hainan.gov.cn/>). At the selected stations, the daily SSD data from 1965 to 1973 was incomplete for some stations, so the missing years' daily SSD was reconstructed using the sediment rating curve before subsequent analyses. The TC data from 1960 to 2022 were collected from the Registered Typhoon Dataset of Hainan Island (Li et al., 2023), including information such as central pressure, wind speed, and latitude and longitude position. Typhoon data for 2023 were obtained from the China Typhoon Network (<https://www.typhoon.org.cn/>).

2.3. Research methods

2.3.1. TC selection

Considering that over 70% of the TC events on Hainan Island occur in the period from July to October, and that the water discharge and SSD of the three rivers account for a significant proportion of the annual totals during this period, this study focuses on the changes in water discharge and SSD caused by TCs during the period from July to October. According to the climate operational regulations of Hainan Province, when the center of a TC moves into the area between 15° and 23°N, and 106° and 114°E, or when it forms in this area, it is classified as a TC that has an impact on Hainan Island (Xue et al., 2018). We first identified TCs that markedly affected the river basin. Then, the daily water discharge and precipitation data from the five stations were combined to further screen out the TCs that markedly induced rapid increases in water discharge and SSD. Daily water discharge at a station exceeded 1.5 times the baseline average, and daily SSD must exceed 2 times the baseline average. The exceedance must persist for at least one consecutive day. Here, the baseline was defined as the average daily water discharge and SSD over the 7 days preceding the TC event, representing typical non-TC river conditions. Events meeting all criteria were classified as substantially influencing the river basins, while those failing to meet the thresholds were excluded. For example, TC Rose in 1968 entered the affected area on August 12 and exited on August 14. The daily water discharge and SSD at all five stations increased markedly, as detailed in Supplementary Fig. S1. Therefore, TC Rose was selected for analysis of its potential contribution to water discharge and SSD at the five stations. On the contrary, the hydrological response induced by TC (unnamed) in 1968 was relatively weak, so this TC was excluded. Finally, 92 TCs that markedly affected the

Table 1
Classification of hydrological years.

TC condition	River	Hydrological condition	Time
TC year	Wanquan River	Flood year	1960 1964 1970 1972 1973 1978 1989 2000 2009 2010 2013
		Normal year	1962 1963 1965 1967 1971 1974 1975 1976 1979 1980 1981 1983 1984 1985 1986 1988 1992 1994 1995 1996 2001 2002 2005 2007 2008 2011 2014 2016 2018 2019 2020 2021 2023
		Dry year	1968 1969 1977 1987 1991 2003
	Nandu River	Flood year	1960 1963 1964 1967 1972 1973 1978 2000 2009 2010 2011
		Normal year	1962 1965 1970 1971 1974 1975 1976 1979 1980 1981 1983 1984 1985 1986 1988 1989 1994 1995 1996 2001 2002 2003 2007 2008 2013 2014 2016 2018 2019 2021 2023
		Dry year	1968 1969 1977 1987 1991 1992 2005 2020
	Changhua River	Flood year	1963 1964 1973 1975 1978 1989 1991 1994 1996 2001 2002 2009 2011 2014 2018
		Normal year	1960 1962 1965 1967 1970 1971 1972 1974 1976 1980 1981 1983 1984 1985 1986 1988 1992 1995 2000 2003 2005 2008 2010 2013 2016 2021
		Dry year	1968 1969 1977 1979 1987 2007 2019 2020 2023
	Non-TC year	Flood year	1990 1997
		Normal year	1961 1982 1993 1999 2006 2012 2017 2022
		Dry year	1966 1998 2004 2015
Non-TC year	Wanquan River	Flood year	1990 1997 2022
		Normal year	1961 1982 1993 1999 2012 2017
		Dry year	1966 1998 2004 2006 2015
	Nandu River	Flood year	1990 1997 2022
		Normal year	1961 1982 1993 1999 2012 2017
		Dry year	1966 1998 2004 2006 2015
	Changhua River	Flood year	1990 1997 2004 2006 2012 2022
		Normal year	1961 1966 1982 1993 1998 1999 2015 2017
		Dry year	1961 1966 1982 1993 1998 1999 2015 2017

Note: A year with an annual water discharge higher than the 75th percentile is defined as a flood year, while a year lower than the 25th percentile is a dry year.

five stations were selected according to the above screening criteria (Supplementary Fig. S2).

2.3.2. Sediment rating curve

The relationship between water discharge (Q_w) and SSD (Q_s) is typically expressed as a nonlinear power function, known as a sediment rating curve (Mouri et al., 2014). This study adopts the widely used form:

$$Q_s = aQ_w^b$$

where a and b are fitted coefficients. We established basin-specific rating curves by performing least-squares regression on the paired daily Q_w (m^3/s) and Q_s (t/d) records. Subsequently, these calibrated curves were applied to the complete daily water discharge time series during the core TC season (July–October) to reconstruct a continuous, gap-free record of SSD. This reconstruction is essential for quantifying total sediment fluxes and analyzing event-scale dynamics, particularly for periods where direct sediment measurements were unavailable or unreliable during high-flow events.

2.3.3. Classification of hydrological years

A “TC year” refers to a year during the typhoon season (July–October) in which the watershed is affected by at least one tropical cyclone; a “Non-TC year” refers to a year in which the watershed is not affected by any tropical cyclones. Extreme hydrological events can be defined as flow values that exceed the 75th percentile or fall below the 25th percentile within the observed years. In this study, years with annual water discharge higher than the 75th percentile are defined as flood years, while years with lower than the 25th percentile are defined as dry years; the rest are normal years (Dai et al., 2016) (Table 1).

2.3.4. Coefficient of variation

The coefficient of variation (CV) is an effective tool for comparing the distribution of different units (Brown, 1998). To identify the variability of a series of water discharge and SSD, the hydrological variation coefficient of CV is calculated based on the daily flow from July to October (Fig. 4). Its calculation formula is:

$$CV = \frac{\sigma}{\bar{R}}; \sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (R_i - \bar{R})^2}; \bar{R} = \frac{1}{n} \sum_{i=1}^n R_i$$

where n is the length of the time series, R_i is the flow in the i -th month, and $\bar{R}$ is the average monthly flow within a year, and σ is the standard deviation of the monthly flows within the year. As the CV value increases, the distribution of monthly flows within the year becomes more uneven.

2.3.5. Contributions of TCs to water discharge and SSD

To quantify the additional water discharge and SSD attributable to TC forcing, we estimated the net TC contribution relative to background non-TC conditions. The net contribution of TCs to the runoff in a year is expressed by P_c , the calculation method of percentile values follows Dai et al., (2016), and the formula is as follows:

$$P_c = \frac{(Q_{w,tc} \times D_{tc} - Q_{w,nor} \times D_{tc}) \times 24 \times 3600}{Q_{w,a} \times D_a \times 24 \times 3600}$$

where $Q_{w,tc}$ (m^3/s) denotes the mean water discharge during TC-affected periods from July to October each year, $Q_{w,nor}$ (m^3/s) represents the mean water discharge during non-TC days from July to October each year, $Q_{w,a}$ (m^3/s) is the annual mean water discharge, D_{tc} (days) is the duration of the relevant TCs, and D_a (days) is 365 or 366. The numerator of the formula represents the absolute contribution of TCs, where the denominator represents the total annual water discharge. The P_c of SSD is calculated similarly.

2.3.6. TC-induced growth rate of water discharge and SSD

To quantitatively reflect the direct impact of TCs on water discharge and SSD and eliminate the impact of the basic discharges of normal days, the growth rate (P_g) is calculated by the following formula:

$$P_g = \frac{Q_{w,tc} - Q_{w,nor}}{Q_{w,nor}}$$

where $Q_{w,tc}$ and $Q_{w,nor}$ have the same meanings as those shown in the contribution formula. The growth rate of SSD in each TC year is computed similarly.

3. Results

3.1. Characteristics of water–sediment cycle changes

Wavelet analysis can provide the instantaneous driving force of the sequence over time and can be used to identify phenomena such as periodic mutations and phased enhancements (or reductions) of the same frequency component (Peng et al., 2020). Wavelet analysis

of water discharge and SSD across the five hydrological stations (July–October, 1960–2023) revealed coherent, multi-scale periodicities within each river basin, underscoring the integrated nature of catchment-scale hydrological responses. The results demonstrate strong intra-basin synchronization, where dominant cycles were highly consistent between upstream and downstream stations. Within the Wanquan River basin, water discharge at both the JJ and JB stations exhibited significant periodicities at approximately 5–7 years and 11–15 years (Fig. 2). SSD at these sites showed analogous 5- and 11-year cycles. These shared periodicities highlight the close correspondence between water discharge and SSD across interannual to decadal timescales. For the Nandu River, water and sediment series at LT and ST stations shared dominant oscillations in short-term (3–5 year), medium-term (11–15 years), and long-term (27–29 years). For the BQ River, water and sediment series shared dominant oscillations in short-term (3–5 year), medium-term (11–15 years), and long-term (23–27 years).

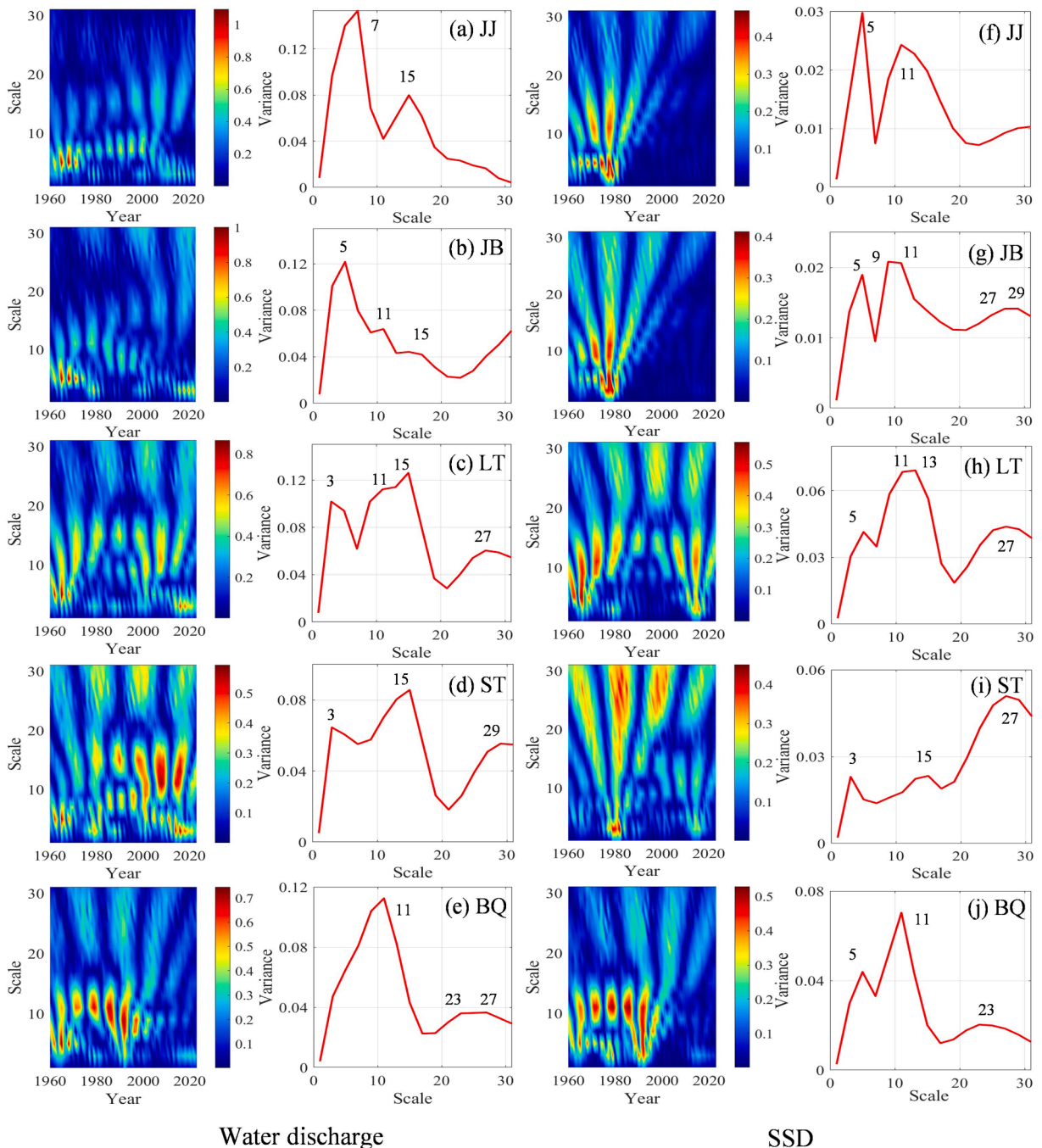


Fig. 2. Wavelet analysis of the annual average water discharge and SSD at each station from 1960 to 2023. Panels (a–e) represent the water discharge at the JJ, JB, LT, ST, and BQ stations, and panels (f–j) represent SSD at the JJ, JB, LT, ST, and BQ stations. Each subfigure includes the continuous wavelet transform (left) and wavelet variance (right); the peaks indicate the dominant time scales at each station.

year) bands. The temporal evolution and intensity of these cycles were remarkably congruent between the two stations. In contrast, the BQ station on the Changhua River displayed a distinct periodicity structure, with synchronous 11- and 23-year cycles governing both water discharge and SSD. The presence of approximately 11- or 15-year oscillations at all stations suggests a common regional climate driver, while the longer-period signals unique to LT, ST, and BQ stations indicate basin-specific modulation of sediment transfer dynamics.

3.2. Variations in water discharge and SSD in non-TC years

Analysis of non-TC periods (July–October) reveals that SSD across all five stations was moderately synchronous with water discharge variations (Fig. 3), suggesting precipitation as an important driver of sediment mobilization under ordinary climatic conditions. The daily SSD consistently exhibited greater variability than water discharge, as indicated by higher average CV at all sites (Fig. 4), underscoring the heightened sensitivity of SSD to hydrological fluctuations. Spatial heterogeneity was evident in both the

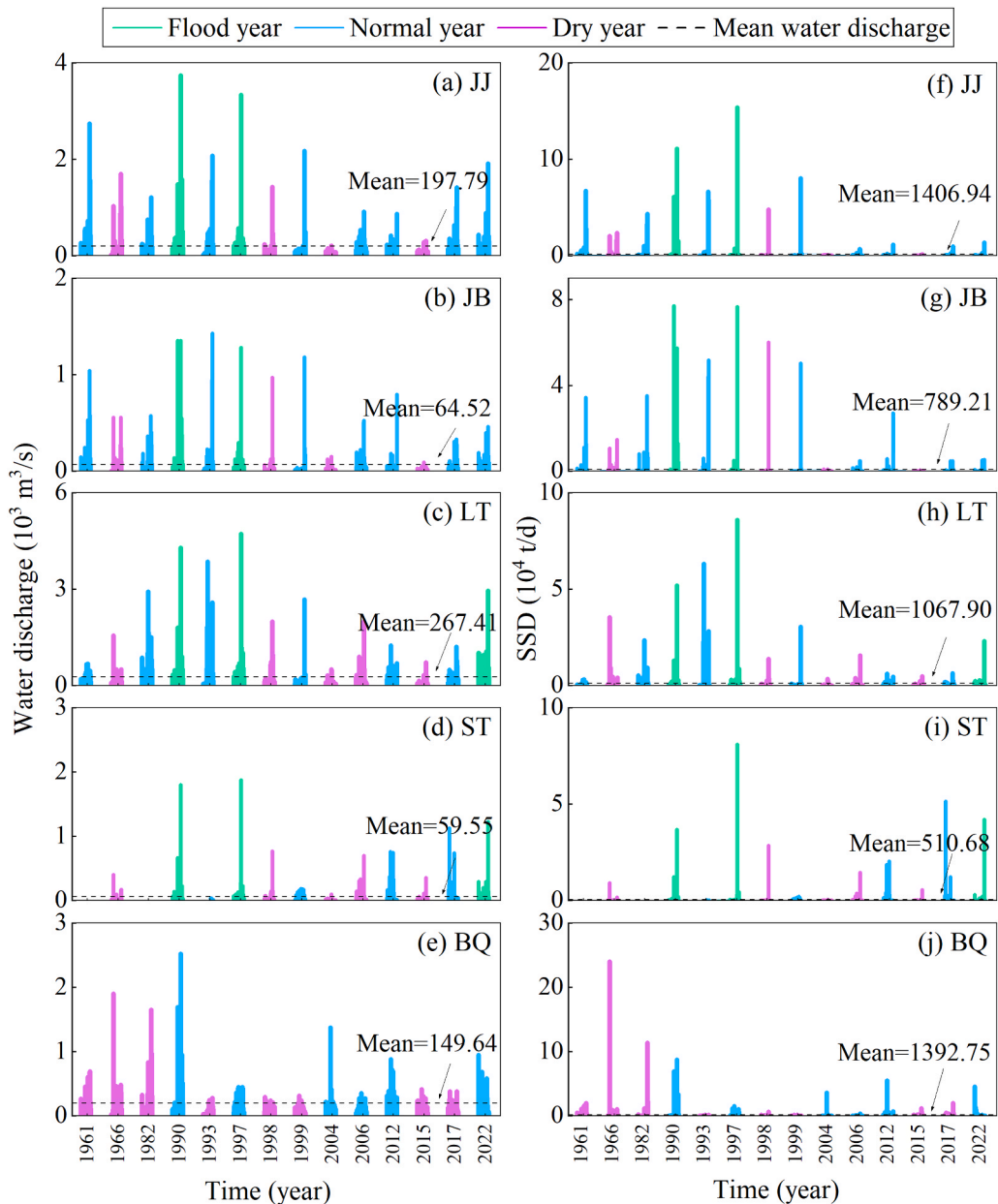


Fig. 3. The daily water discharge and SSD variations from July to October in non-TC years. Panels (a–e) represent the water discharge at the JJ, JB, LT, ST, and BQ stations, while panels (f–j) represent SSD at the JJ, JB, LT, ST, and BQ stations.

magnitude and variability of responses. Downstream stations (JJ and LT) recorded higher mean water discharge and SSD than their upstream counterparts (JB and ST). Notably, the Wanquan River basin displayed the most dynamic water–sediment coupling: JB station showed the greatest variability in daily water discharge ($CV = 0.63$), while JJ station exhibited the highest variability in SSD ($CV = 1.13$). Further segmentation by hydrological conditions (flood, normal, and dry years) showed that water discharge was more evenly distributed during dry years compared to flood and normal years across all basins. A striking temporal synchronicity was observed between major flood events in the Nandu and Wanquan rivers during non-TC years. In contrast, the BQ station (Changhua River) did not experience a defined flood year under these conditions, highlighting its distinct hydrological regime.

3.3. Variations in water discharge and SSD under the influence of TCs

During TC years, water discharge and SSD across all monitored stations were substantially amplified compared to non-TC years, with flood-year values markedly exceeding those in normal and dry years (Fig. 5). The daily hydrographs in TC years exhibited similarly rapid fluctuations as in non-TC periods, but with substantially greater magnitudes. The response to TCs was spatially heterogeneous: the JJ (Wanquan River) and LT (Nandu River) stations exhibited the most pronounced increases in both water discharge and SSD, whereas changes at the JB (Wanquan River) and ST (Nandu River) stations were comparatively subdued, particularly between dry and normal years. Analysis revealed distinct inter-basin patterns in sediment delivery efficiency under TC forcing. Although the Nandu River at LT station carried the highest mean water discharge, its average daily SSD (1813.98 t) was relatively moderate. In striking contrast, the Changhua River at BQ station, despite a much lower mean water discharge ($244.43 \text{ m}^3/\text{s}$), transported an average daily SSD of 6179.52 t. This represents a sediment yield 3.4 times greater than the Nandu River and 2.2 times greater than the Wanquan River (JJ station), identifying the Changhua River as the most efficient sediment conveyor during TCs. For both the Nandu and Wanquan rivers, mean water discharge and SSD at downstream stations (LT and JJ) were substantially higher than at their upstream counterparts (ST, JB), indicating substantial sediment contribution and transport along the main channels. Finally, the variability of hydrological responses shifted under TC influence. Compared to non-TC years, the average CV for daily water discharge across stations was generally higher during TC years. Conversely, the CV values for SSD showed less pronounced change between the two periods (Fig. 4), suggesting that while TC events amplify the absolute magnitude of sediment transport, the relative variability of

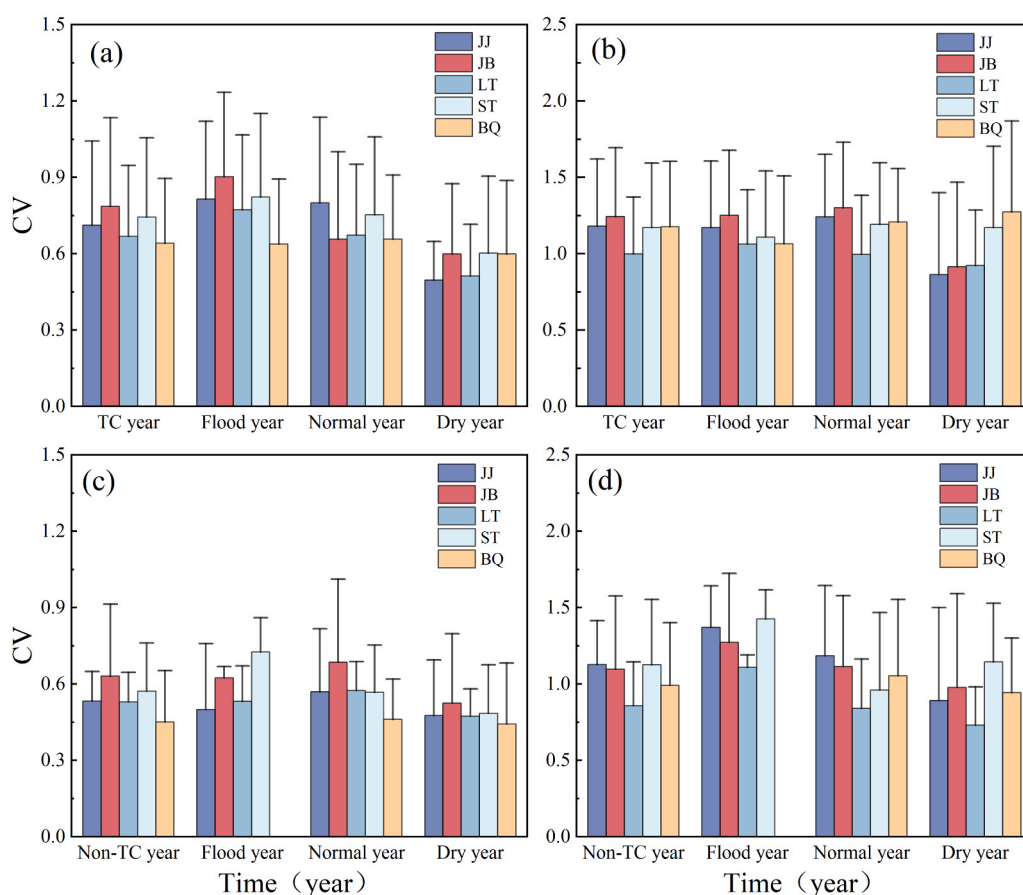


Fig. 4. The CV values of water discharge and SSD for the five stations under different hydrological conditions from 1960 to 2023. Panels (a) and (c) represent the water discharge, while (b) and (d) represent SSD.

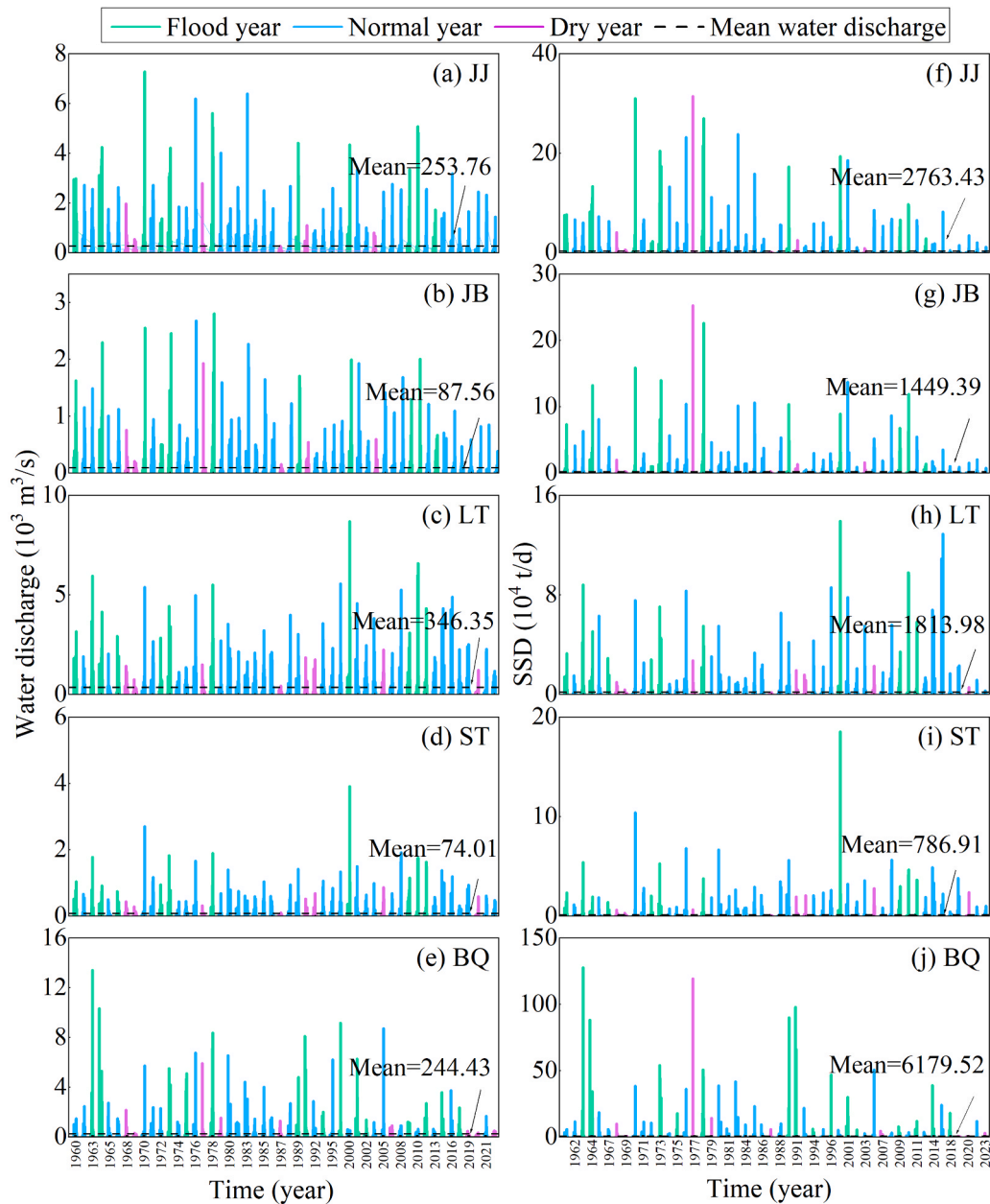


Fig. 5. Changes in daily water discharge and SSD from July to October of the TC year. Panels (a–e) represent the water discharge at the JJ, JB, LT, ST, and BQ stations, while panels (f–j) represent SSD at the JJ, JB, LT, ST, and BQ stations.

sediment delivery remains within a consistent range.

To isolate and quantify the impact of TCs, we partitioned the July–October daily water and sediment records into TC-event days and non-TC days. Despite their short duration (typically 2–3 days), TC events disproportionately amplified both daily mean water discharge and SSD by orders of magnitude compared to non-event days (Fig. 6), establishing TCs as a major control on the seasonal flux regime. The response exhibited strong interannual and spatial heterogeneity. Annual totals from TC days showed pronounced interannual fluctuations, whereas contributions from non-TC periods remained relatively stable. The Nandu River at ST station displayed the most sensitive response, with TC-event water discharge averaging 6.4 times that of non-TC days. Along the Nandu River from ST (upstream) to LT (downstream), mean TC-day water discharge increased markedly from 416.74 to 1140.67 m³/s, while SSD increased only modestly from 8536.79 t to 10,776.19 t. This pattern indicates efficient downstream convergence of flow but a relative decline in sediment transport efficiency per unit of water. Notably, SSD responded more sharply to TC forcing than water discharge. At all stations, the average SSD during TC periods exceeded non-TC levels by an order of magnitude. The annual SSD series exhibited a distinct pulse-like, intermittent nature, where the extreme peaks in record years were almost entirely attributable to sediment

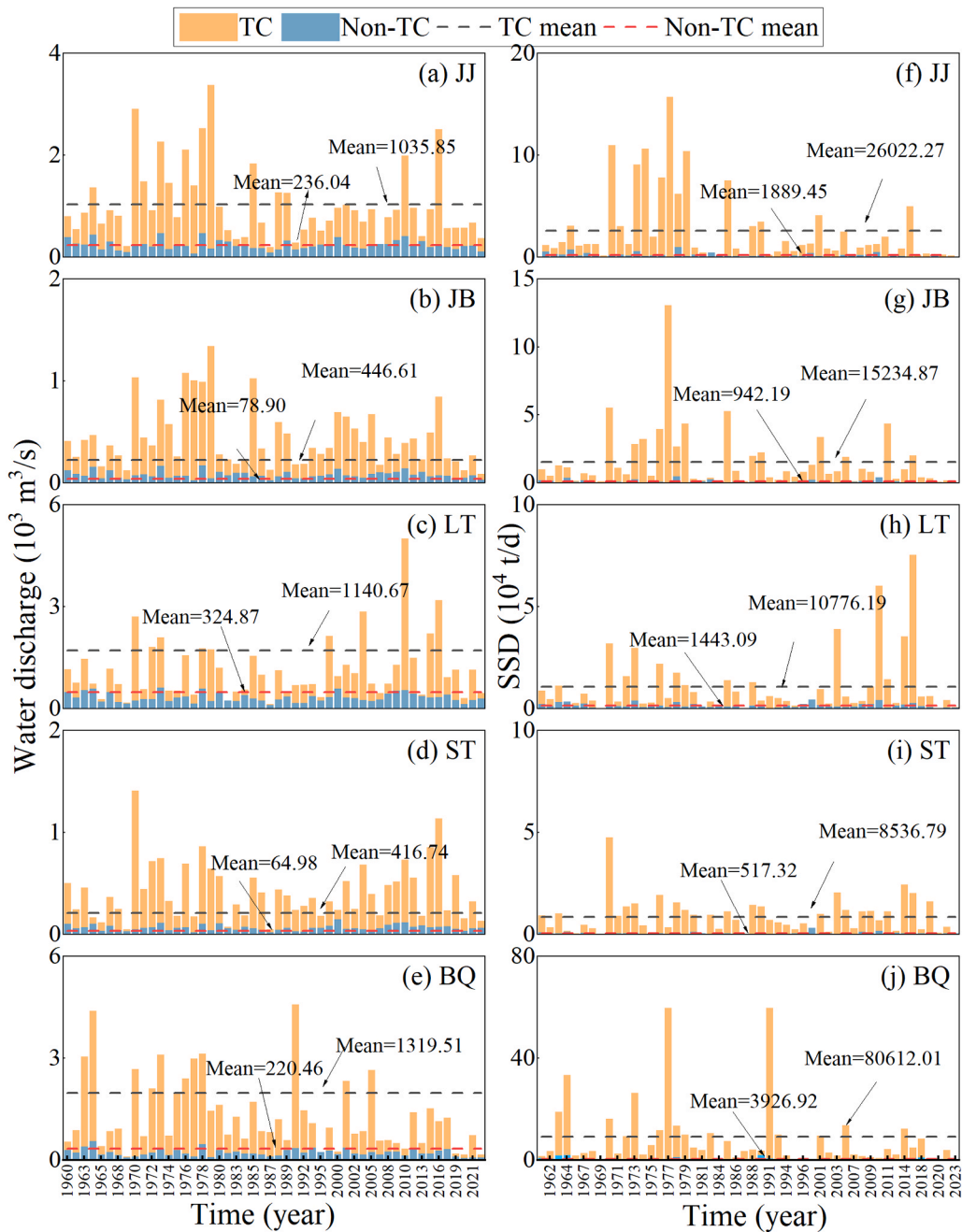


Fig. 6. Daily average water discharge and SSD at five stations on TC days and normal days. Panels (a–e) represent the water discharge at the JJ, JB, LT, ST, and BQ stations, while panels (f–j) represent SSD at the JJ, JB, LT, ST, and BQ stations.

mobilized during brief TC windows.

3.4. Relationship between water discharge and SSD on TC days versus normal days

Sediment discharge dynamics across the five monitored stations are well described by a robust power-law relationship with water discharge ($SSD = aQ^b$), which holds for both TC and non-TC periods ($p < 0.001$; Fig. 7). The scaling exponent (b), indicative of sediment transport efficiency, is generally lower during TC days, revealing that the highest flows do not proportionally yield the highest sediment concentrations. Detailed analysis of the parameters (a , b) delineates three distinct basin response patterns to TC forcing: 1) Enhanced Initial Mobilization with Attenuated Efficiency. At downstream stations JJ (Wanquan River), BQ (Changhua

River), and ST (Nandu River), the coefficient a for TC days is substantially higher (e.g., 0.0324 vs. 0.0016 at JJ), signifying greater sediment availability or erosion at moderate flows. However, the exponent b is lower (1.30 vs. 1.64 at JJ), indicating that sediment transport efficiency during peak TC flows is ultimately surpassed by that of non-TC floods. This pattern suggests TC acts as a concentrated scouring pulse. 2) Lower Sediment Transport Efficiency during TC Events. At station LT (Nandu River), both parameters are lower during TC days (a : 0.0021 vs. 0.0032; b : 1.52 vs. 1.62). This suggests a scenario where TC events do not markedly enhance sediment transport efficiency, with both the initial sediment concentration and transport efficiency at high flows being lower during TC days compared to normal days. This indicates that the impact of TC events on sediment transport may be constrained by other factors. 3) Threshold-Triggered Explosive Efficiency. At upstream stations JB (Wanquan River), the TC-period coefficient a is markedly

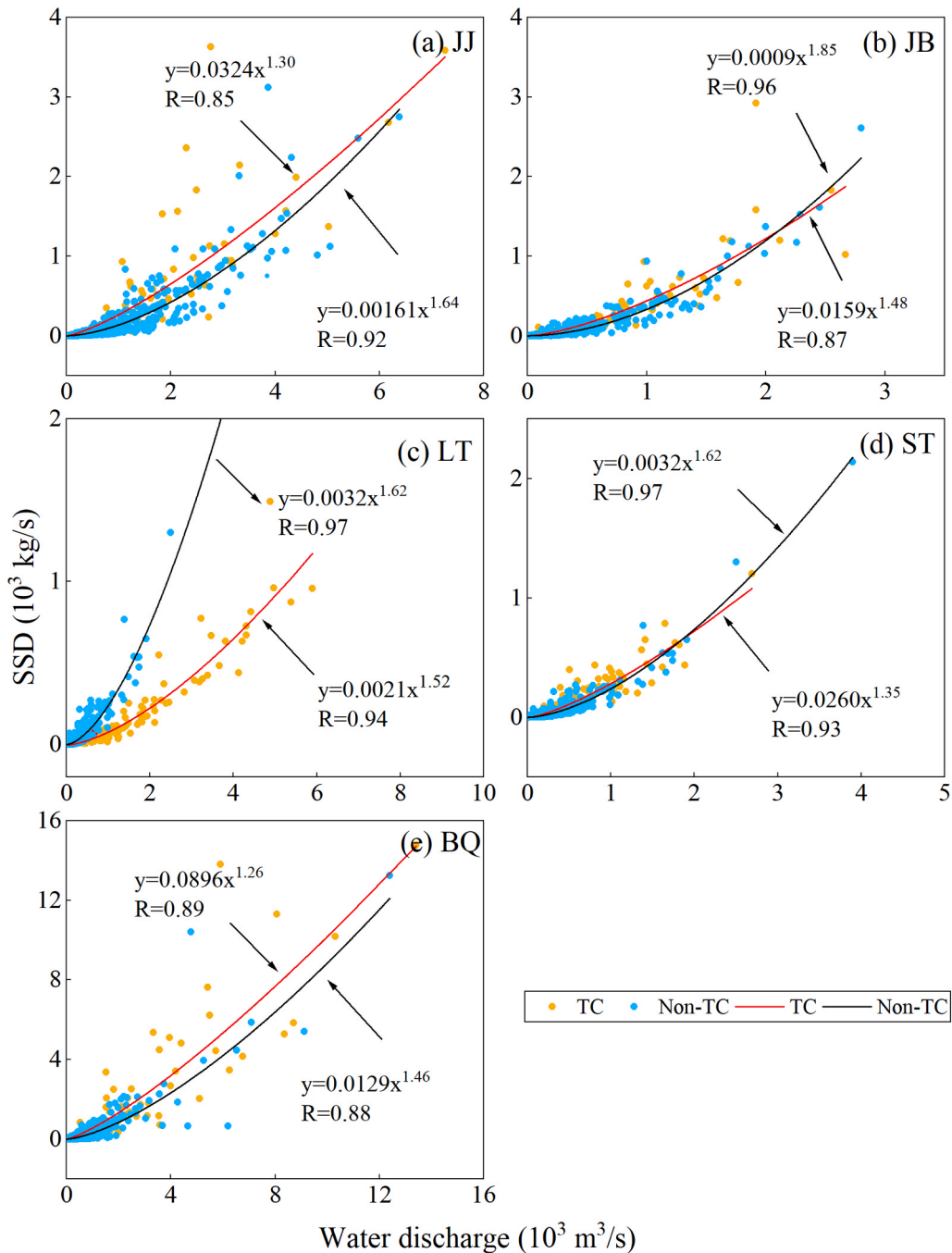


Fig. 7. Relationships between daily water discharge and SSD on TC days and normal days. Panels (a–e) represent stations JJ, JB, LT, ST, and BQ, respectively.

lower (e.g., 0.0009 vs. 0.0159 at JB), implying limited initial mobilization. Conversely, the exponent b is exceptionally high (1.85 vs. 1.48 at JB), pointing to a threshold-dominated system where extreme TC discharges are required to access and rapidly mobilize distal sediment sources.

3.5. Contribution of TCs to water discharge and SSD

Our quantitative analysis reveals that while TCs are episodic, they exert a disproportionate influence on the annual sediment budget compared to their impact on water discharge. From 1960–2023, the contribution of TCs to total annual water discharge was relatively modest and stable across the five stations (Fig. 8). The average contribution ranged from a low of $4 \pm 4\%$ at LT station (Nandu River) to a high of $8 \pm 6\%$ at JB station (Wanquan River), with peaks reaching 24–25% in extreme years such as 1976. In stark contrast, TCs dominate the annual SSD, demonstrating their primary role as sediment-mobilizing agents (Fig. 9). The average TC contribution to SSD was markedly higher, ranging from $11 \pm 10\%$ at LT to $30 \pm 27\%$ at BQ station (Changhua River). In extreme years, this contribution became overwhelming; for example, in 1977, TCs accounted for 91–95% of the annual SSD at JB and JJ stations. The

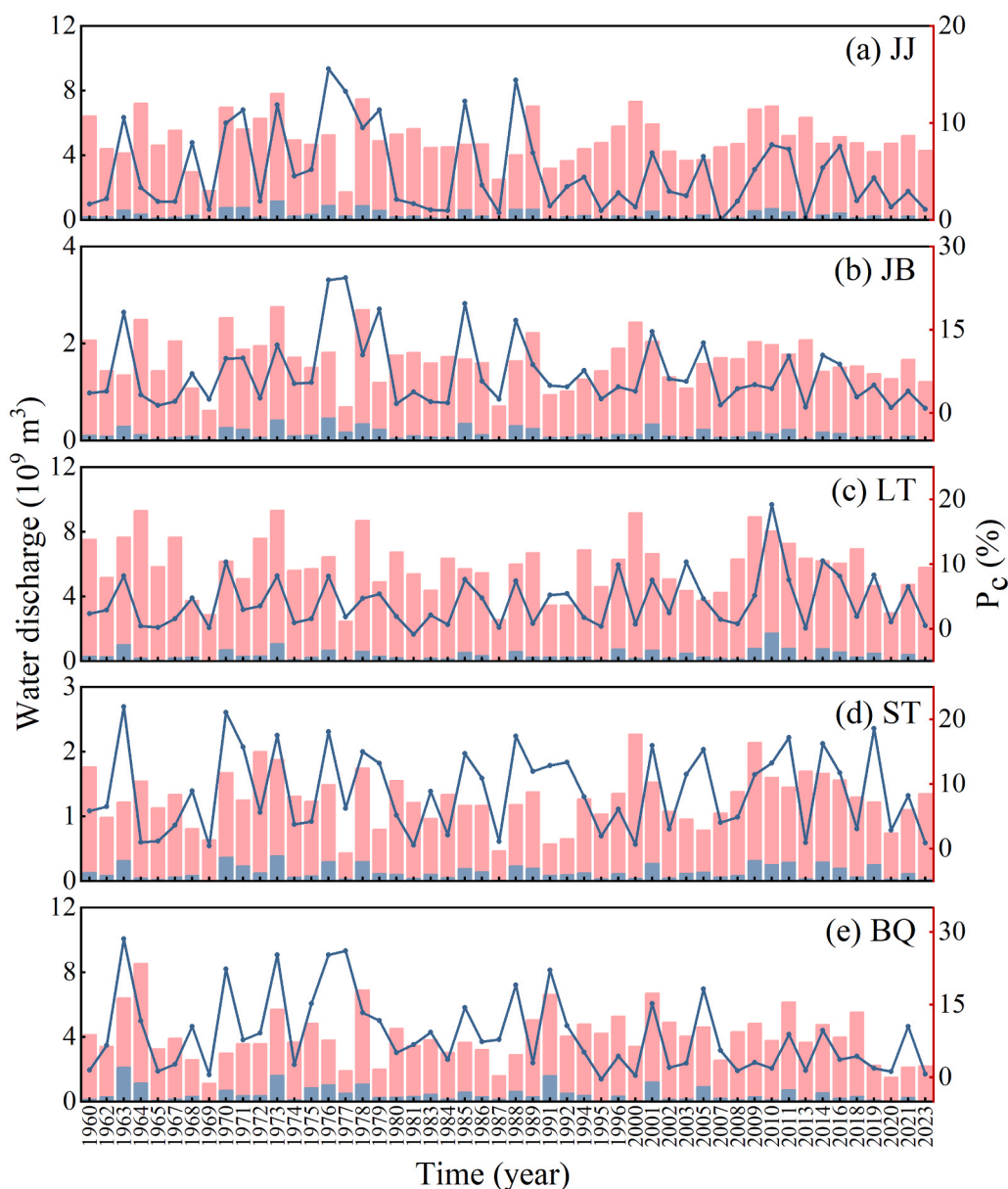


Fig. 8. Net contribution of TCs to water discharge. Panels (a–e) represent stations JJ, JB, LT, ST, and BQ, respectively. Light gray represents the water discharge generated by TCs, pink represents the total annual water discharge, and the blue solid line represents the contribution rate.

Changhua River (BQ station) exhibited the most intense interannual variability in its sediment response to TCs. Furthermore, a pronounced upstream-downstream disparity was observed within the Nandu River basin. The long-term average contribution of TCs to ST station was 27%, whereas the long-term average contribution to downstream LT station was only 11%, indicating a strong modulation of the TC sediment signal along the river corridor—a phenomenon explored in the subsequent discussion.

4. Discussion

4.1. Impact from precipitation

The important control of precipitation, particularly its frequency and intensity, on both water discharge and SSD is confirmed by

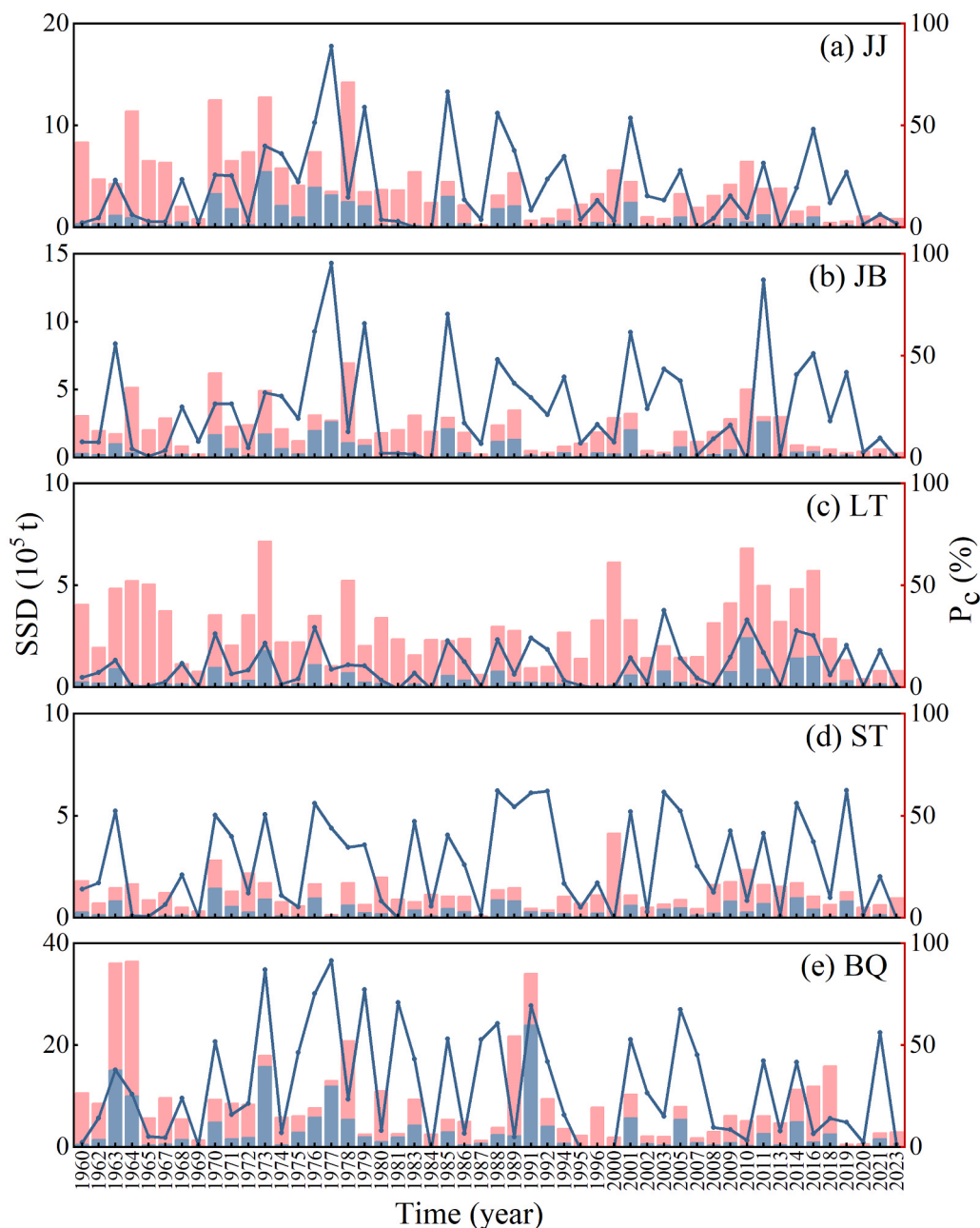


Fig. 9. Net contribution of TCs to SSD. Panels (a–e) represent stations JJ, JB, LT, ST, and BQ, respectively. Light gray represents the SSD generated by TCs, pink represents the total SSD per year, and the blue solid line represents the contribution rate.

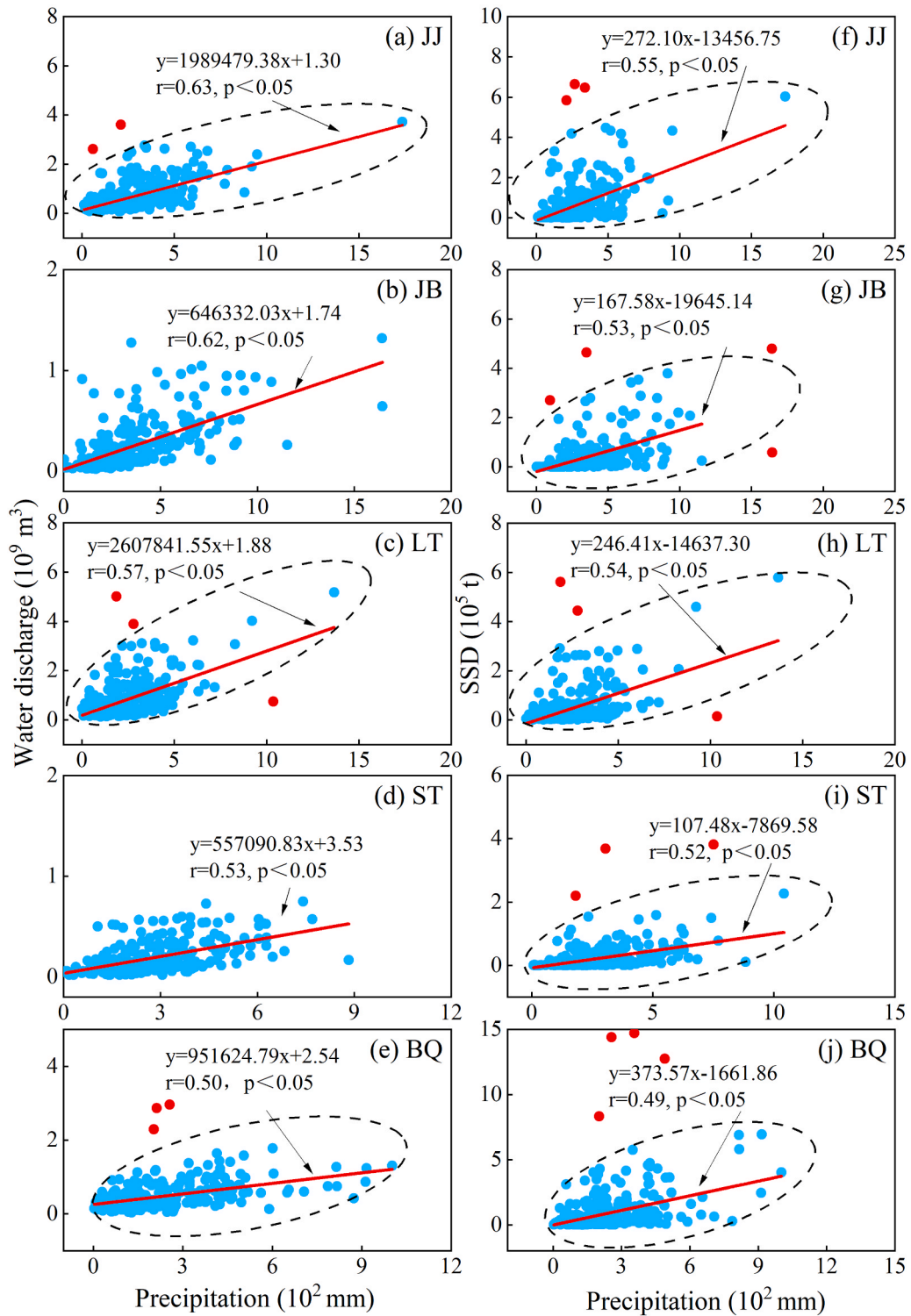


Fig. 10. The relationship between monthly precipitation, water discharge and SSD for the five stations from 1960 to 2023 in July to October. Panels (a–e) show the relationships between precipitation and water discharge at the JJ, JB, LT, ST, and BQ stations, respectively; panels (f–j) show the relationships between precipitation and SSD at the same stations. The data outside the ellipse is not used for linear fitting.

markedly positive correlations at all five stations (Fig. 10; Chang et al., 2023). The linear fit is primarily based on most typical precipitation events (blue points) to reveal the overall sensitivity trends of water discharge and SSD to precipitation, while certain extreme events (red points) are retained in the figure to reflect their nonlinear response characteristics. However, the sensitivity of the response varies: water discharge at JJ and LT exhibits a more sensitive reaction to precipitation compared to the relatively gentler response at ST station. Notably, the correlation between precipitation and SSD is generally weaker than for water discharge, suggesting that SSD is modulated by a more complex set of non-precipitation factors, such as topography and sediment supply. This interpretation is consistent with previous studies showing that storm-period sediment loads depend strongly on the availability and spatial connection of erodible sediment sources, rather than only on flow magnitude (Tian et al., 2023).

This supply-limited mechanism helps explain why TC-driven extreme flows do not always generate proportionally extreme sediment loads (Fig. 7). During intense TC events, high runoff can exceed the threshold for mobilizing hillslope, bank, and channel-stored sediment, leading to a short-term amplification of sediment transport relative to water discharge. Similar disproportionate sediment responses have been reported in typhoon-affected mountainous rivers, where extreme rainfall can rapidly activate landslides, bank erosion, and channel sediment storage (Chen et al., 2020). Nevertheless, such amplification may weaken once readily transportable sediment is depleted or when long-term soil conservation and vegetation recovery reduce sediment supply. This is also consistent with the established view that sediment yield is regulated by both effective precipitation and vegetation-mediated sediment production, rather than by rainfall amount alone (Langbein and Schumm, 1958).

The distinct behavior of water and sediment is further elucidated by analyzing their event-scale growth rates (Fig. 11). Water discharge growth rates typically fluctuate within a low-to-medium range. By comparison, SSD growth rates exhibit greater variability and more pronounced peaks, suggesting that SSD can be more sensitive to extreme forcing under favorable sediment-supply conditions. This pattern is consistent with previous studies on typhoon-affected rivers, which have shown that extreme storms can amplify sediment export relative to water discharge when flood power exceeds the entrainment threshold and sufficient mobilizable sediment is available (Hung et al., 2018). Sensitivity varied among stations, being highest at JB and BQ stations (largest peak amplitudes), moderate at ST station (frequent, moderate peaks), and most stable at LT station, with JJ station showing an intermediate but occasionally high response. This hierarchy of sensitivity underscores that the pulsed delivery of sediment is the hallmark of TC impact, governed by thresholds in sediment supply and transport capacity that vary markedly across basins.

4.2. Impacts from TC characteristics

Wavelet analysis of key parameters (air pressure and wind speed) for 92 tropical cyclones affecting Hainan Island from 1960 to 2023 was conducted, with the average value of multiple cyclones used to represent that year if multiple cyclones occurred in the same year. The results revealed significant multi-scale periodicities at 5, 9–11, and approximately 29 years (Fig. 12). These periodicities are broadly comparable to the characteristic timescales of large-scale ocean-atmosphere oscillation, with the interannual (5 year) signal falling within the characteristic timescale of ENSO variability and the longer-period signals showing temporal similarities to low-frequency climate modes such as the PDO (Tang et al., 2024). This multi-scale periodicity in TC meteorology shows remarkable spectral coherence with the identified cycles in riverine water and sediment fluxes (cf. Fig. 2), indicating that the wind speed of tropical

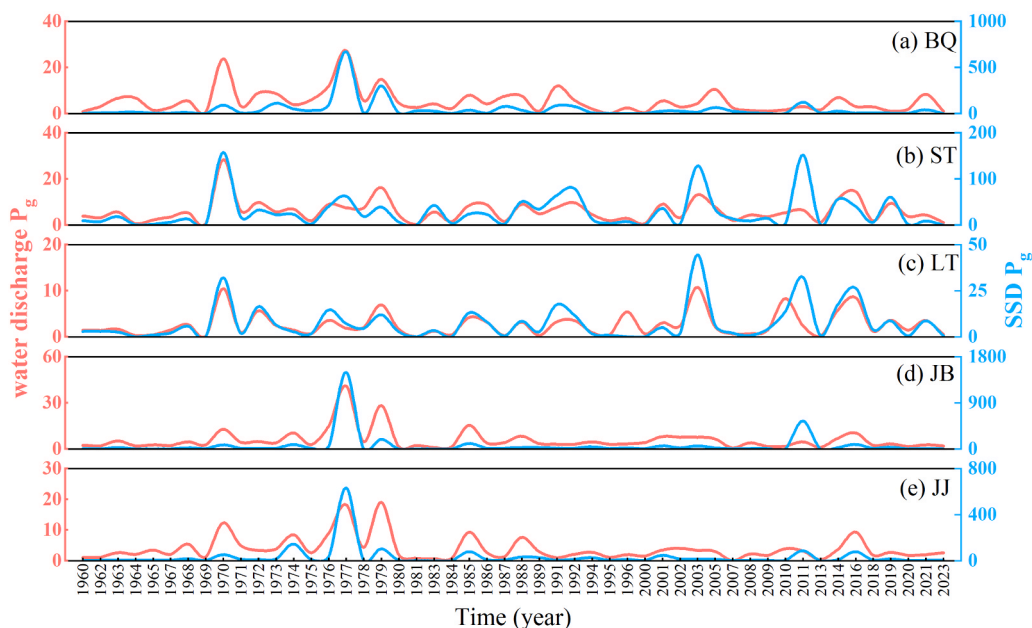


Fig. 11. The water discharge growth and SSD growth rates at five stations. Panels (a–e) represent stations BQ, ST, LT, JB, and JJ, respectively.

cyclones influences the water–sediment processes in the basin at different time scales. In addition to the enhanced water discharge resulting from increased precipitation, the wind-driven mixing of the water body also plays an important role. Strong winds not only exacerbate bank erosion but also induce vertical mixing in the water, enhancing the resuspension and transport of sediment. Particularly in estuarine and near-shore areas, the wind-induced mixing reduces sediment settling time, further improving the efficiency of sediment transport.

The wavelet analysis revealed 3–7 year, ~11 year, and 15–29 year periodicities in the hydrological and sediment records. To further evaluate whether these periodicities are associated with large-scale climate variability, we performed correlation analyses between July–October water–sediment variables and three climatic indices: the Niño 3.4 anomaly, the PDO index derived from ensemble SST data, and monthly sunspot numbers. The results indicate that, with the exception of the BQ station, runoff at the other four stations showed a significant negative correlation with ENSO ($P < 0.05$; Fig. 13). This negative correlation suggests that higher ENSO values (corresponding to El Niño conditions) are generally associated with lower runoff from July to October. One possible mechanism is that ENSO modulates tropical cyclone activity, water vapor transport, and regional precipitation patterns in the northwestern Pacific, thereby reducing the precipitation contribution from typhoons or shifting the precipitation center away from Hainan Island. In contrast, the correlations between runoff and sediment records and the PDO or sunspot index were not statistically significant. Therefore, although the approximately 11-year and 15–29-year periodicities are close to the typical timescales of solar activity and PDO variability, respectively, these correspondences should be regarded as temporal similarities rather than evidence of direct climatic forcing. Further analytical studies are needed in the future to verify whether these low-frequency signals have a dynamical link to solar activity or the PDO.

The duration of a TC is an important determinant of its cumulative hydrological impact, with longer-lasting storms typically generating greater total water discharge and SSD—a relationship supported by significant positive correlations at all five stations (Chen et al., 2011). This pattern arises because extended TC duration increases cumulative basin-wide rainfall, which in turn elevates total runoff and the window for sediment mobilization. The sensitivity to TC duration, however, varies spatially, as revealed by the

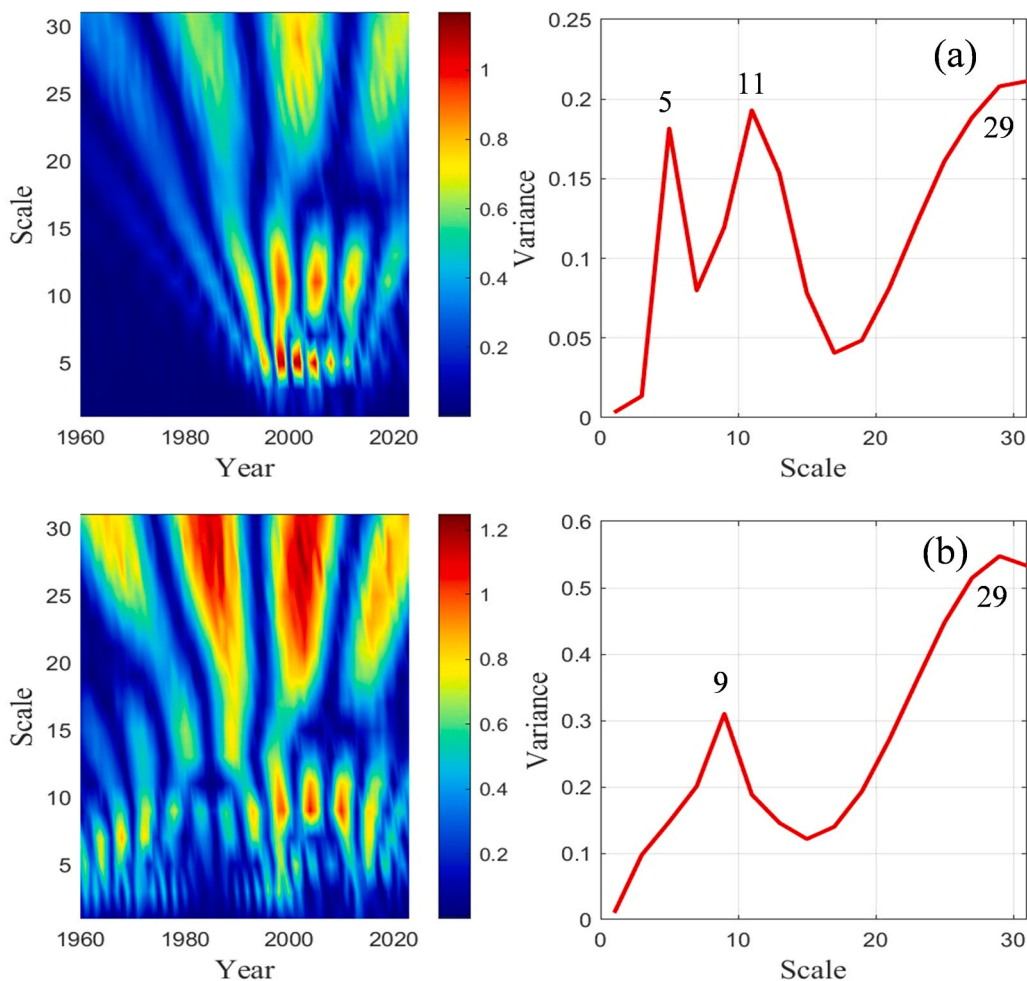


Fig. 12. Wavelet analysis of maximum pressure and maximum wind speed of 92 TCs from 1960 to 2023. Panel (a) represents the maximum air pressure, and panel (b) represents the maximum wind speed.

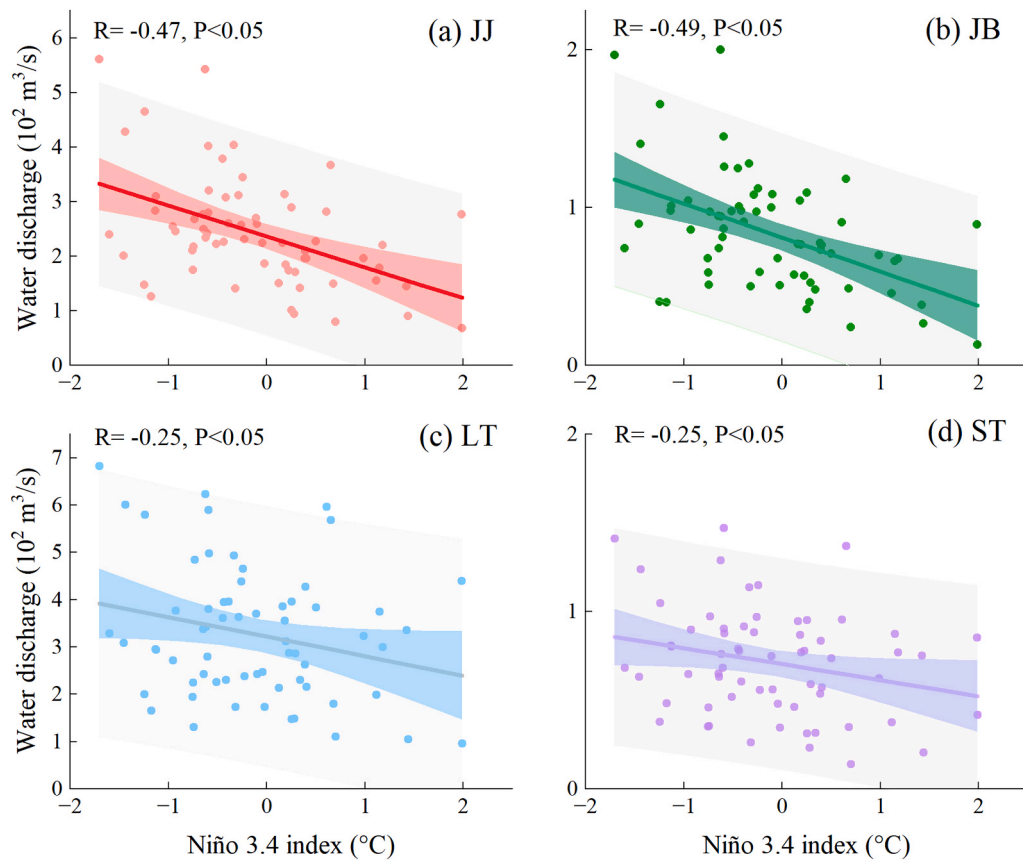


Fig. 13. Relationships between annual water discharge and the Niño 3.4 anomaly from 1960 to 2023. Panels (a–d) represent stations JJ, JB, LT, ST, respectively.

slope of these relationships. Downstream stations exhibit a markedly stronger response. For instance, the slopes for water discharge at BQ station (2014.48) and LT station (1272.90) are the highest (Fig. 14), likely due to their larger catchment areas which integrate runoff over longer flow accumulation times. Similarly, for SSD, BQ station shows the greatest sensitivity (slope = 129,746.73), potentially reflecting enhanced channel erosion and sediment resuspension processes in the lower reaches. In contrast, upstream stations like JB (slope = 19,154.47) and ST (slope = 13,657.33) demonstrate a more attenuated SSD response to storm duration. This unique pattern, alongside the presence of prominent high-value outliers in the data, underscores a key conclusion: while TC duration is an important governing factor, it is not the sole determinant of the water discharge and SSD. The ultimate flux is modulated by a confluence of other dynamic factors, including TC intensity and rainfall spatial distribution, antecedent watershed wetness, and basin-specific characteristics such as topography and land cover, which collectively filter the TC signal.

4.3. The regulatory role of the river basin environment

The comparative analysis reveals distinct hydro-sedimentary response regimes among the three major rivers, governed by a combination of physiographic and anthropogenic factors. To examine these controlling factors, we have created spatial distribution maps depicting the hydrological, climatic, and topographic characteristics of Hainan Island (Fig. 15).

The Nandu River exhibits the highest water discharge growth rate (8.8; Fig. 11), indicating the most rapid hydrological response to TC rainfall. Although the main channel gradient of the Nandu River is generally lower than that of the Wanquan River (Fig. 15d), the Nandu River basin has the largest catchment area (Fig. 15c), which efficiently integrates runoff (Fig. 15a), and its higher average annual precipitation relative to the Changhua River basin further enhances runoff generation. However, the sediment response of the Nandu River is not proportional to its hydrological response. The relative attenuation of sediment transport from ST to LT is the result of the combined effects of sediment retention by reservoirs, riverbed deposition, and spatial variations in precipitation. The Songtao Reservoir, located upstream of both the ST and LT stations, traps a substantial amount of sediment, thereby reducing the sediment supply delivered to the downstream river system. Since its completion, approximately 700,000 t of sediment have accumulated upstream of the dam each year, indicating a substantial reservoir-trapping effect on downstream sediment delivery. At the same time, the downstream section at LT features gentle topography and a low riverbed gradient, resulting in reduced flow velocity and diminished sediment transport capacity. Consequently, some suspended sediment settles on the riverbed and floodplains during transport,

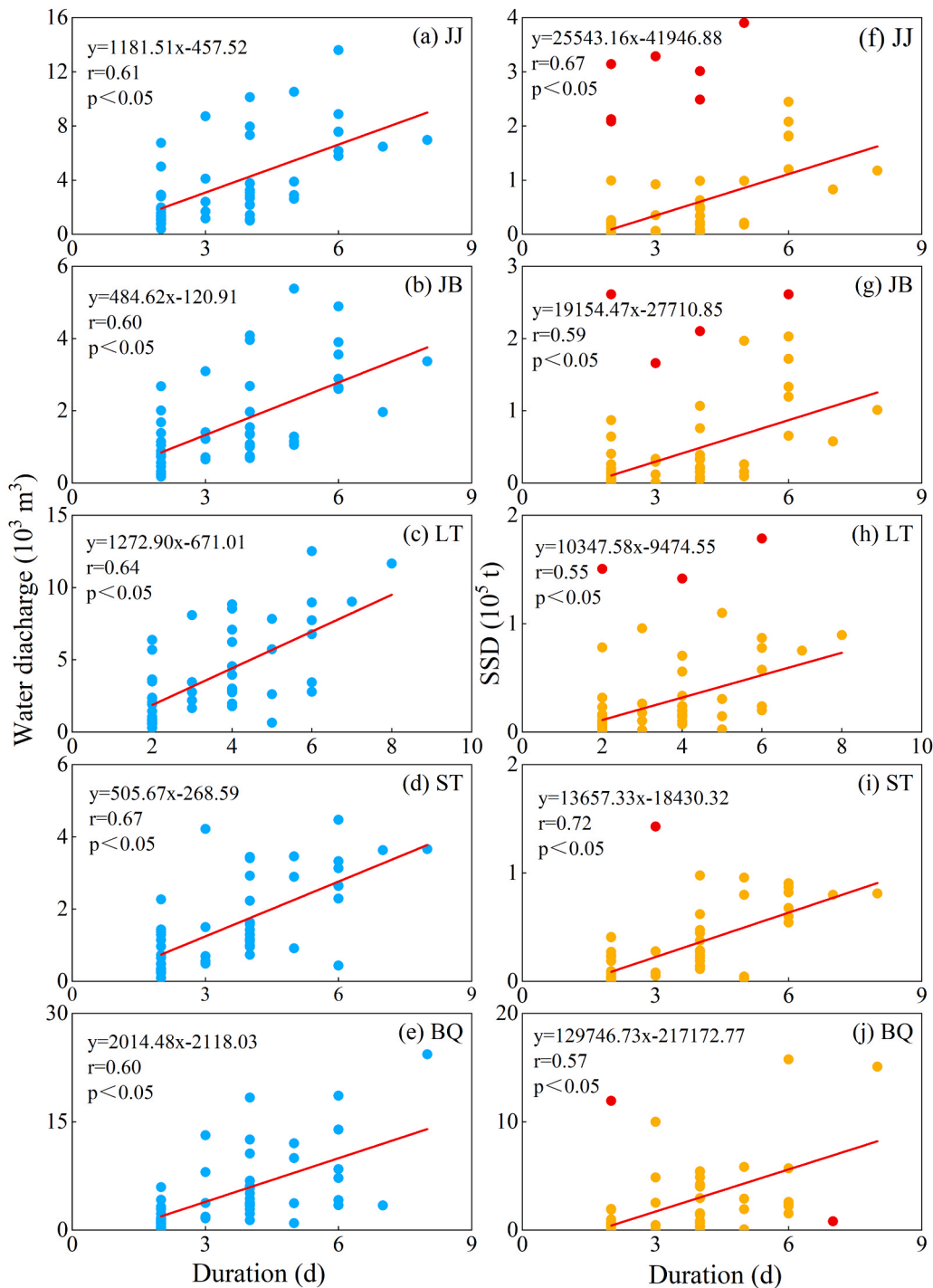


Fig. 14. Relationship between the duration of TCs from July to October and water discharge and SSD from 1960 to 2023. Panels (a–e) represent the relationships between TC duration and water discharge at stations JJ, JB, LT, ST, and BQ, respectively, while panels (f–j) show the corresponding relationships between TC duration and SSD. The red dots in the figure represent peak events of SSD anomalies, which were not included in the linear regression fit.

contributing to a weaker increase in sediment discharge relative to the increase in water discharge from ST to LT. Furthermore, relatively low precipitation in the middle and lower reaches of the Nandu River weakens runoff and scouring capacity, further limiting sediment transport downstream.

The contrast between the Changhua River and the Wanquan River further highlights the role of climatic and geomorphic gradients.

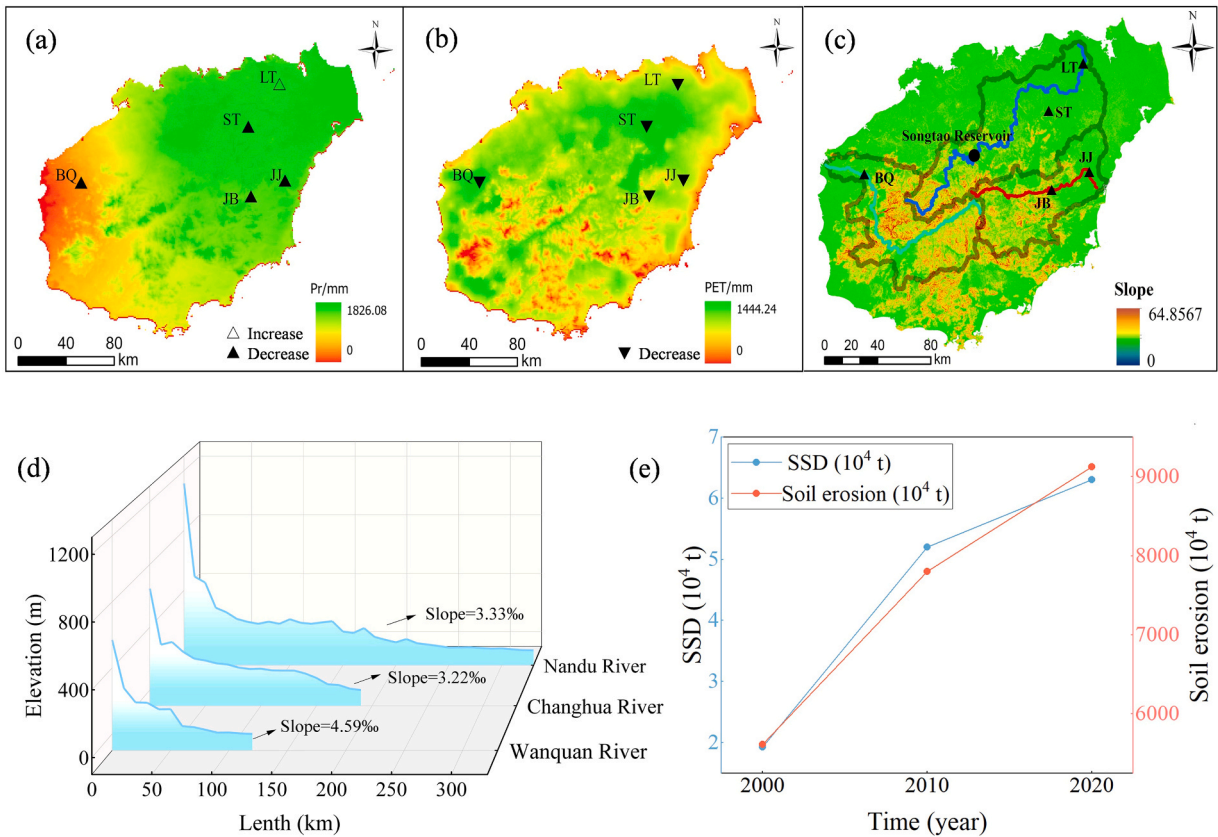


Fig. 15. Spatial distribution and temporal trends of hydroclimatic and geomorphological factors in Hainan Island. Panels (a–c) show the spatial distributions of mean annual precipitation, potential evapotranspiration, and slope, respectively. Panel (d) shows the longitudinal profiles and channel slopes of the Nandu River, Changhua River, and Wanquan River. Panel (e) compares the annual SSD observed at the BQ station with estimated soil erosion.

Despite having a larger basin area than the Wanquan River, the Changhua River at BQ station records a lower mean annual water discharge ($231.11 \text{ m}^3/\text{s}$ vs. $243.32 \text{ m}^3/\text{s}$ at JJ). This apparent paradox is resolved by considering the regional climatic and hydrogeological gradient: the eastern Wanquan basin receives higher precipitation and experiences lower evaporation than the western Changhua basin, where greater evaporative losses and potentially higher infiltration capacity reduce effective runoff (Fig. 15a, b). Nevertheless, the Changhua River is identified as the most efficient sediment transporter. This efficiency stems from a combination of severe soil erosion within its basin and a distinct seasonal sediment supply cycle. In terms of soil erosion in areas with severely degraded vegetation, the Changhua River basin has the largest affected area (15.71 km^2), followed by the Nandu River basin (14.95 km^2), while the Wanquan River basin has the smallest (7.48 km^2) (Zou, 2023). The upper reaches of the Changhua River basin exhibit a marked expansion of construction land in rural areas, while the lower reaches are currently dominated by artificial lakes, construction land, and bare land. This phenomenon has reduced vegetation cover in the region, and the land-use conversion process has exacerbated soil erosion. We compared and validated the observed annual sediment discharge data from the BQ Hydrological Station on the Changhua River in Hainan Island with the estimated soil erosion rates in the Changhua River basin for the years 2000, 2010, and 2020 (Fig. 15e). The soil erosion rates for the three years were $56.14 \times 10^6 \text{ t}$, $78.03 \times 10^6 \text{ t}$, and $91.27 \times 10^6 \text{ t}$, respectively, while the measured sediment discharge was $1.93 \times 10^4 \text{ t}$, $5.20 \times 10^4 \text{ t}$, and $6.23 \times 10^4 \text{ t}$, respectively. From 2000–2020, both soil erosion rates and measured sediment discharge showed an overall increasing trend, and their annual trends were consistent. Although the absolute amount of measured sediment discharge is much smaller than the total estimated soil erosion, their consistent increasing trends suggest that enhanced basin-scale soil erosion provided an increasing sediment source for riverine transport.

Furthermore, reservoir regulation is not the only human activity affecting sediment transport. Long-term soil and water conservation, vegetation restoration, land-use adjustments, slope stabilization, and other watershed management measures can markedly reduce sediment input by increasing surface roughness, enhancing infiltration, reducing slope erosion, and weakening the connectivity between slopes and river channels (Chen et al., 2023; Hu et al., 2017; Liu et al., 2020). Even under conditions of high runoff or high rainfall erosivity, these processes can reduce sediment outflow. Therefore, observed sediment trends should not be interpreted solely as a result of total runoff or channel kinetic energy. Rather, they reflect the combined effects of multiple factors, including climate-driven changes, topographic transport capacity, reservoir retention, soil erosion intensity, and changes in sediment supply resulting from human activities. Since the three basins studied in this research lack continuous quantitative records of vegetation restoration and soil

and water conservation measures, this paper discusses these influences as potential moderating factors of sediment supply. Future research should integrate long-term land use/land cover data, vegetation indices, soil and water conservation records, and reservoir operation data to further distinguish between hydrological control factors and anthropogenic sediment supply control factors.

5. Conclusion

This study quantifies the dominant role of TCs in governing the episodic fluxes of water discharge and SSD in the mountainous rivers of Hainan Island. We reveal that TCs are the key driver of fluvial processes during the core typhoon season (July–October), with their intensity, path, and duration critically modulating hydrological responses. While their contribution to total annual water discharge is relatively modest, TCs disproportionately control the sediment budget, accounting for the overwhelming majority of SSD in extreme years and underscoring their primacy in landscape denudation. Our analysis reveals a complex, non-linear water–sediment relationship. Although increased water discharge generally enhances SSD, peak flows do not yield proportionally peak sediment loads. We identify distinct catchment response patterns to TC forcing—ranging from concentrated scouring with attenuated efficiency to threshold-triggered explosive mobilization—highlighting how basin-specific factors (e.g., sediment availability, channel morphology) filter the TC signal. Significant differences in TC sensitivity exist among the three major rivers. The Nandu River exhibits the strongest response to TC forcing, linked to its large catchment area and higher precipitation. In contrast, the Changhua River demonstrates the greatest sediment transport efficiency, a consequence of its steeper gradients, severe soil erosion, and distinct seasonal sediment supply dynamics. These differential responses are fundamentally modulated by an interplay of TC characteristics, basin physiography (area and slope), and anthropogenic interventions, most notably the sediment-trapping effect of major reservoirs such as the Songtao, which markedly attenuates the downstream sediment signal.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ejrh.2026.103906](https://doi.org/10.1016/j.ejrh.2026.103906).

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